社団法人 電子情報通信学会
THE INSTITUTE OF ELECTRONICS,
INFORMATION AND COMMUNICATION ENGINEERS

信学技報
TECHNICAL REPORT OF IEICE

DS-CDMA 下りリンクにおける基地局選択ダイバーシチ送信とアンテナ受信ダイバーシチの併用効果

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あらまし　本論文では，総送信電力一定の条件下で DS-CDMA 下りリンクの容量を最大とする送信方法は，チャネル利得が最大となる基地局より送信する基地局選択ダイバーシチ送信（SSDT）であることを理論的に示している．また，モンテカルロシミュレーション法によってリンク容量を求め，瞬時チャネル利得に基づく瞬時 SSDT がリンク容量を最大とすることを確認している．さらに，平均チャネル利得に基づく平均 SSDT についても検討し，両者の違いとリンク容量に及ぼす影響について明らかにしている．

キーワード　DS-CDMA，SSDT，SHO，リンク容量，レイク合成

Forward Link Performance of Site Selection Diversity Transmit with Antenna Diversity and Rake Combining in DS-CDMA Mobile Radio

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Abstract　In this paper, it is theoretically shown that the optimal solution to maximize the DS-CDMA forward link capacity under the condition of constant total transmit power is to transmit only from the best base station (BS) that has the maximum channel gain (this is called site selection diversity transmit (SSDT)). This theoretical analysis is confirmed by the Monte-Carlo computer simulation　of an instantaneous SSDT which is based on instantaneous channel gain. In addition we also consider the case of average power based SSDT to study the difference of these two types of SSDT and their effects on forward link capacity.

Keyword　DS-CDMA, SSDT, SHO, link capacity, rake combining

1. Introduction

DS-CDMA is used for multiple access in 3rd generation cellular systems due to its high spectrum efficiency. The flexibility of sharing the same frequency also yields the option of site diversity. In cellular systems, the service area is divided into many cells, where each of the cells has a BS in the cell center to serve users in the respective cell [1]. However, the distance dependent path loss, shadowing and fast fading cause a rapid fluctuation of radio signal level received at the mobile station (MS). The probability of the received signal power failing to achieve the required signal quality is called outage probability. In our paper, the link capacity is defined as the maximum number of users that can communicate simultaneously under the allowable outage probability. Near the cell's boundaries, the outage probability is high. However, remembering that the signals transmitted from two or more BS's are received at nearly equal levels near a cell boundary, the same data is sent simultaneously towards a target user from two or more BS's and is combined by the user's receiver to improve the transmission performance. This technique is called site diversity and is incorporated into soft hand-off (SHO) which is helpful in a handoff transition from one cell to another [2].

Multiple site transmission required for SHO causes a possible increase of interference that may outweigh site diversity gain. Therefore, recent work focuses on SSDT for DS-CDMA forward link channel. For instance in [3], the effect of TPC combined with SSDT, where the best BS is dynamically chosen as the transmitting side and the output power of other BS's is reduced in forward link, has already been studied. However, the theoretical aspect of SSDT is yet to be analyzed. Therefore, in this paper, we first present the theoretical base of SSDT and then it is followed by computer simulation.

The remainder of this paper is organized as follows. The next section describes the system model under consideration. The principle of an instantaneous as well as an average SSDT based on this model is also presented here. The theoretical aspect of SSDT is discussed in Sect. 3. In Sect. 4, the performance evaluation is done by the Monte-Carlo computer simulation for various system parameters. Finally, the paper is concluded with Sect. 5.

2. System Model

It is assumed that the service area consists of 19 identical hexagonal cells as illustrated in Fig. 1. The BS is located at the center of each cell. The users are assumed to be uniformly distributed over the entire area. In Fig.1, i denotes the cell index and $j(i)$ denotes the jth MS located in the ith cell. The i=0th cell is the cell of interest. $r_{i,j(0)}$ is the normalized distance by cell radius R between the BS of ith cell and jth MS of 0th cell, $\eta_{i,j(0)}$ is the shadowing loss expressed in dB between the BS of ith cell and jth MS of 0th cell. It is assumed that the propagation channel consists of L discrete propagation paths having time delays of integer multiple of DS-CDMA chip duration, each being subjected to independent Rayleigh fading and that rake combining can resolve all L paths to coherently combine them based on maximal ratio combining (MRC) [4].

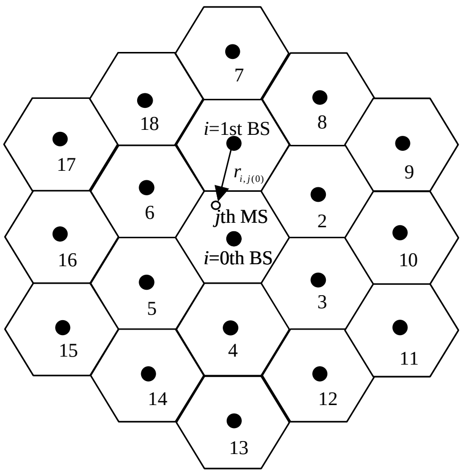

Fig. 1 Cellular structure under consideration.

2.1. Mathematical Representation of Received Signal Power

In mobile wireless communication, the propagation channel can be modeled as the multiplication of distance dependent path loss, log-normally distributed shadowing loss and fading. The received signal power at the jth MS of 0th cell based on this model can be represented as

$$S_{R_{i,j(0)}} = S \cdot L_{i,j(0)} \cdot \left|\xi_{i,j(0)}\right|^2 \quad , \qquad (1)$$

where the normalized transmit power S and average link gain $L_{i,j(0)}$ between ith cell and jth MS of 0th cell are defined as

$$\begin{cases} S = S_T \cdot R^{\alpha} \\ L_{i,j(0)} = r_{i,j(0)}^{-\alpha} 10^{-\frac{\eta_{i,j(0)}}{10}} \end{cases} , \qquad (2)$$

where the shadowing loss $\eta_{i,j(0)}$ expressed in dB is assumed to be a Gaussian process with zero mean and standard deviation σ of about 4 to 10, α is the path loss exponent, ξ is the equivalent fading gain observed at the rake combiner output, S_T is the transmit power from the BS. Throughout the paper, transmit power refers to the normalized one defined in Eq. (2) and notation S is used to represent that.

2.2. Principle of SSDT

The system model described in the previous section is an approach of modeling the real environment, where the number of cells is not confined to 19. However, based on this model, SSDT can be explained. In the computer simulation, we focus on the centered cell, where outage probability is measured for each MS. Before starting the communication, an MS first sorts out the BS's in descending order out of 19 cells based on average link gain, as $L_{k=0,j(0)} \geq L_{k=1,j(0)} \geq \ldots \geq L_{k=K-1,j(0)}$, and then the first K BS's are selected. The set of first K cells from the sorted BS's is defined as the active set. While a communication is in progress, the MS selects BS from the active set based on instantaneous received signal power. In order to do this, the BS's of the active set are again sorted out in descending order and Q BS's are selected as follows:

$$L_{q=0,j(0)}\left|\xi_{q=0,j(0)}\right|^2 \geq L_{q=1,j(0)}\left|\xi_{q=1,j(0)}\right|^2 \geq \ldots \geq L_{q=Q-1,j(0)}\left|\xi_{q=Q-1,j(0)}\right|^2,$$

where $\xi_{q,j(0)}$ is the equivalent fading channel gain after rake combining with M-antenna diversity combining for the communication link between the BS of qth cell and jth MS of 0th cell and can be expressed as [5]

$$\left|\xi_{q,j(0)}\right|^2 = \sum_{m=0}^{M-1}\sum_{l=0}^{L-1}\left|\xi_{q,j(0)}(m,l)\right|^2 \quad , \qquad (3)$$

where $\xi(m,l)$ is the lth path gain experienced by the mth antenna which is characterized as a zero mean complex Gaussian process. The first Q BS's transmit the signal to the MS and those transmitted signals are received and combined at the MS receiver. With more than one cell in the active set (K>1), the case Q=1 is defined as instantaneous SSDT, while Q>1 is called SHO. However if the number of cells, K, is set to be 1 in the active set, the case Q=1 will be the average power based SSDT.

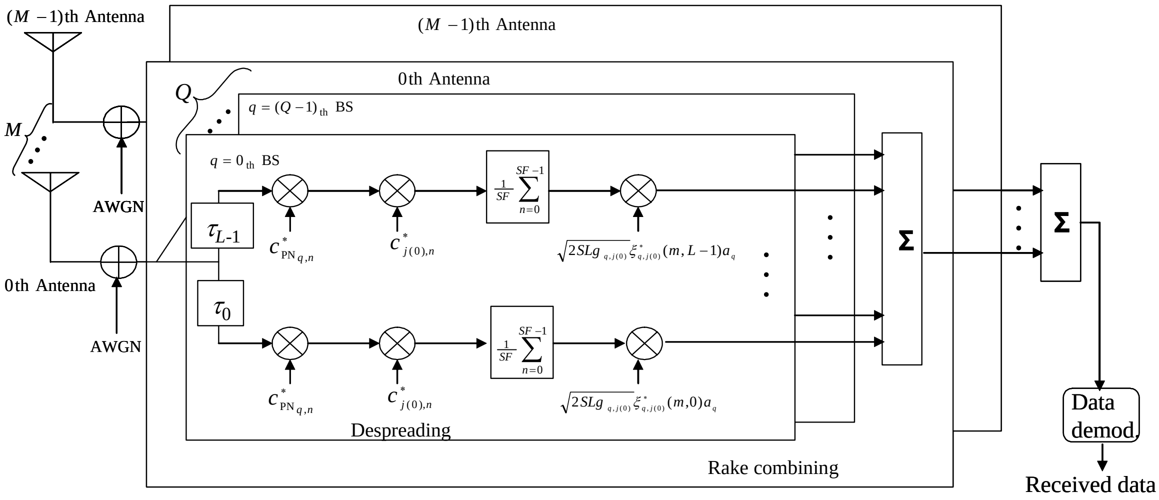

Fig.2 Mobile receiver block diagram.

3. SSDT: A Theoretical Perspective

Fig. 2 shows the block diagram of a mobile rake receiver where forward link (from BS to MS) multipath signals from multiple BS's are processed. Quadrature phase shift keying (QPSK) data modulation and binary PSK (BPSK) spreading modulation are assumed. The transmit signal from the qth BS is expressed using equivalent lowpass representation as

$$s_q(t)=\sqrt{2S}\sum_{j=0}^{U_q-1} d_j(t)c_{PN_q}(t)c_j(t)a_q(t)\,, \qquad (4)$$

where $d_j(t)$, $c_{PN_q}(t)$, $c_j(t)$ and $a_q(t)$ are respectively given by

$$\begin{cases} d_j(t)=\sum_{g=-\infty}^{\infty} d_{j,g}u(t/T-g) \\ c_{PN_q}(t)=\sum_{n=-\infty}^{\infty} c_{PN_{q,n}}u(t/T_c-n) \\ c_j(t)=\sum_{n=-\infty}^{\infty} c_{j,n}u(t/T_c-n) \\ a_q(t)=\sum_{g=-\infty}^{\infty} a_{q,g}u(t/T-g) \end{cases} . \qquad (5)$$

In the above, $\{d_{j,g}\}$ is the gth transmit QPSK symbol to jth user with $|d_{j,g}|=1$, $\{c_{PN_{q,n}}\}$ is the long code with $\left|c_{PN_{q,n}}\right|=1$ and $\{c_{j,n}\}$ is the orthogonal channelization code with $|c_{j,n}|=1$. The chip rates for both the codes is $1/T_c$, $u(x)$ is unit pulse function with

$$u(x)=\begin{cases} 1 & if \;\; 0\le x\le 1 \\ 0 & \text{otherwise} \end{cases} . \qquad (6)$$

$\{a_{q,g}\}$ is the transmit weight with the following constraint:

$$\sum_{q=0}^{Q-1}\left|a_{q,g}\right|^2=1 \qquad (7)$$

so that the total transmit power of the Q BS's is kept constant which is S. In the following, the subscript g is dropped for the sake of simplicity.

$Q \times L$ transmitted signals are received by M antennas and coherently combined by the rake receiver. The rake combined output is approximated a complex Gaussian random variable with the mean μ and the variance $2\sigma^2$ as

$$\begin{cases} \mu=\sqrt{\frac{E_b}{N_0}}\sum_{q=0}^{Q-1}\left|a_q\right|^2 L_{q,j(0)}\sum_{m=0}^{M-1}\sum_{l=0}^{L-1}\left|\xi_{q,j(0)}(m,l)\right|^2 \\ \sigma^2=\frac{E_b}{N_0}\frac{1}{SF}\sum_{q=0}^{Q-1}\left|a_q\right|^4 U_q L_{q,j(0)}^2\times \\ \qquad \sum_{m=0}^{M-1}\sum_{l'=0}^{L-1}\left|\xi_{q,j(0)}(m,l')\right|^2\sum_{\substack{l=0\\ l\neq l'}}^{L-1}\left|\xi_{q,j(0)}(m,l)\right|^2 \\ \quad +\frac{E_b}{N_0}\frac{1}{SF}\sum_{q=0}^{Q-1}\left|a_q\right|^2 L_{q,j(0)}\sum_{\substack{i=0\\ i\neq q}}^{18}\left|a_i\right|^2 U_i L_{i,j(0)}\times \\ \qquad \sum_{m=0}^{M-1}\sum_{l'=0}^{L-1}\left|\xi_{q,j(0)}(m,l')\right|^2\sum_{l=0}^{L-1}\left|\xi_{i,j(0)}(m,l)\right|^2 \\ \quad +\frac{1}{2}\sum_{q=0}^{Q-1}\left|a_q\right|^2 L_{q,j(0)}\sum_{m=0}^{M-1}\sum_{l=0}^{L-1}\left|\xi_{q,j(0)}(m,l)\right|^2 \end{cases} , \qquad (8)$$

where U_i is the number of users connected to ith cell and E_b/N_0 denotes the transmit signal energy per bit-to-noise power spectrum density ratio, which is given by $0.5ST/N_0$, where N_0 is the additive white Gaussian noise (AWGN) single sided power spectral density. Once we know the mean and the variance, the bit error rate (BER) P_e can be expressed as [4]

$$P_e = \frac{1}{2} erfc\sqrt{\gamma_R} \ , \tag{9}$$

where $\gamma_R = \mu^2/2\sigma^2$ is the received signal-to-interference plus noise power ratio (SINR) and erfc(x) is the complementary function given by

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} \exp(-t^2) dt \ .$$

The received SINR γ_R needs to be maximized to render the P_e minimum, which eventually maximizes the link capacity. If we neglect the interference part, γ_R can be represented by

$$\gamma_R = \frac{E_b}{N_0} \sum_{q=0}^{Q-1} |a_q|^2 h_q \ , \tag{10}$$

where h_q is the equivalent channel gain given by

$$h_q = L_{q,j(0)} \sum_{m=0}^{M-1} \sum_{l=0}^{L-1} \left| \xi_{q,j(0)}(m,l) \right|^2 \ . \tag{11}$$

The optimum transmit weight a_q that maximizes γ_R is obtained below. Letting $\psi = \gamma_R/(E_b/N_0)$, maximization problem of γ_R is equivalent to maximizing

$$\psi = \sum_{q=0}^{Q-1} x_q h_q \ , \tag{12}$$

where

$$x_q = |a_q|^2 \tag{13}$$

with the constraint

$$\sum_{q=0}^{Q-1} x_q = 1 \ . \tag{14}$$

Employing the simplex algorithm for linear programming [6], we obtain (see Appendix)

$$\begin{cases} x_q = \delta_{qv} \\ \psi_{\max} = h_v \ \text{if} \ h_v = \max_{q=\{0,1,\cdots,Q-1\}} \{h_q\} \end{cases} , \tag{15}$$

where δ_{qv} is Kronecker's delta function [7] which is defined by

$$\delta_{qv} = \begin{cases} 1 \ \text{for} \ q = v \\ 0 \ \text{for} \ q \neq v \end{cases} . \tag{16}$$

Eventually, we get the optimum value of a_q and the maximum γ_R as follows

$$\begin{cases} a_q = \delta_{qv} \\ \gamma_R = \frac{E_b}{N_0} h_v \ \text{if} \ h_v = \max_{q=\{0,1,\cdots,Q-1\}} \{h_v\} \end{cases} . \tag{17}$$

Eq. (17) states that signal transmission only from one BS, that has the maximum channel gain among all the BS's in the active set, optimizes site selection technique which is also supported by computer simulation in the following section.

4. Monte-Carlo Simulation

In this section, the link capacity using SSDT is evaluated based on Mote-Carlo simulation. The simulation condition is given at Table 1. As explained in Section 2.1, here the transmit power refers to transmit E_b/N_0. It is assumed that each BS transmits signals with equal power. It is found that at around transmit E_b/N_0=20 dB, the channel gets interference limited. Therefore, throughout this paper, transmit E_b/N_0=20 dB is assumed.

Table 1. Simulation Condition

Modulation scheme	QPSK
Cellular structure	Hexagonal cell
User distribution	Uniform
Path loss exponent	α=3, 3.5, 4
Standard deviation of shadowing loss	σ=4, 6, 8 dB
Multipath fading channel	L-path Rayleigh fading
Rake combining	$Q\times L$-finger coherent Rake combining
Antenna diversity	M-antenna MRC
Required BER	10^{-2}
Spreading factor	SF=64

4.1. Comparison of SSDT and SHO

As noted before, here Q stands for the number of best BS's selected by a particular MS instantaneously from the active set, while a communication is in progress. The optimal transmit weight achieved from the theoretical analysis, set the value of Q as 1, which we have defined as SSDT.

However for the case of Q>1, the so called SHO, the transmit weight attached to all the Q BS's is assumed to be same, that is,

$$a_{q=0} = a_{q=1} = \cdots = a_{q=Q-1} \quad . \quad (18)$$

In Fig. 3, outage probability is plotted against the number of users. This figure shows that with Q=1, the maximum link capacity can be obtained regardless of the number of paths or receive antennas. For instance, in single-path (L=1) environment without antenna diversity reception, link capacity for an allowable outage probability of 0.1 is 7 in case of Q=1, while it is 5 and 4 for Q=2 and 3 respectively with SF=64.

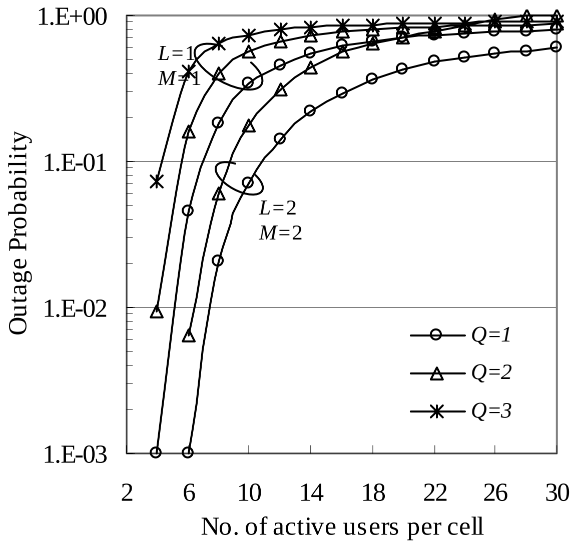

Fig. 3 Comparison of SSDT and SHO for K=7.

4.2. Effect of Instantaneous Site Selection

Fig. 4 shows how the number K of cells in the active set affects the link capacity, where K=1 is the average power based SSDT and K>1 is an instantaneous SSDT. When the value of K increases, the MS can switch between the BS's of active set instantaneously that prevents the received signal from dropping below the desired level. This leads to the decrease of outage probability, which in turn, improves the link capacity. This figure demonstrates this fact where the increase of K especially from K=1 to K=3 presents a significant improvement in the link capacity.

4.3. Effect of Path Loss Exponent and Standard Deviation of Shadowing Loss

Varying the parameters of path loss and shadowing loss, we get Fig. 5 and 6, respectively. Fig. 5 shows that as the value of path loss exponent α increases, the link capacity also increases due to the rapid decaying of interference power at higher α. On the other hand, as for the standard deviation of shadowing loss, we find an opposite result. It is due to the wider fluctuations of signal level at higher σ that causes a possible increase of interference.

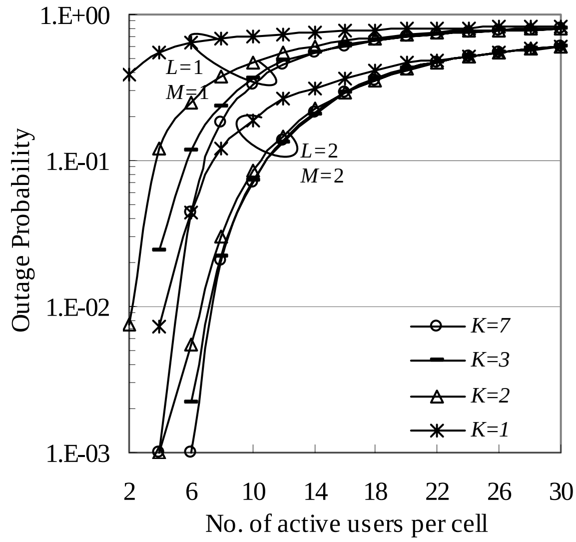

Fig. 4 Effect of no. of cells in active set (K) for Q=1.

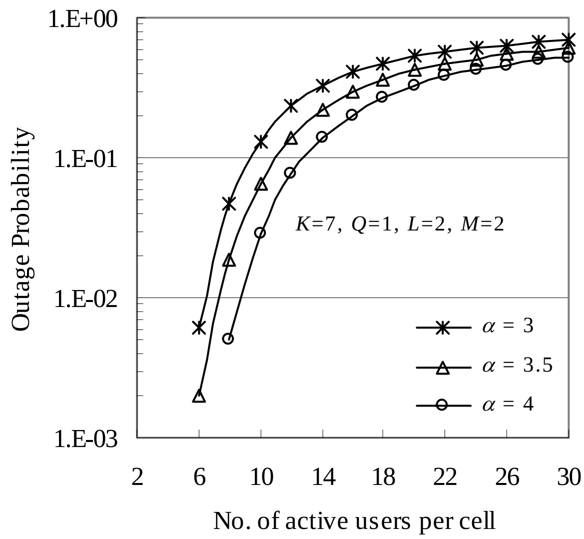

Fig. 5 Effect of path loss exponent.

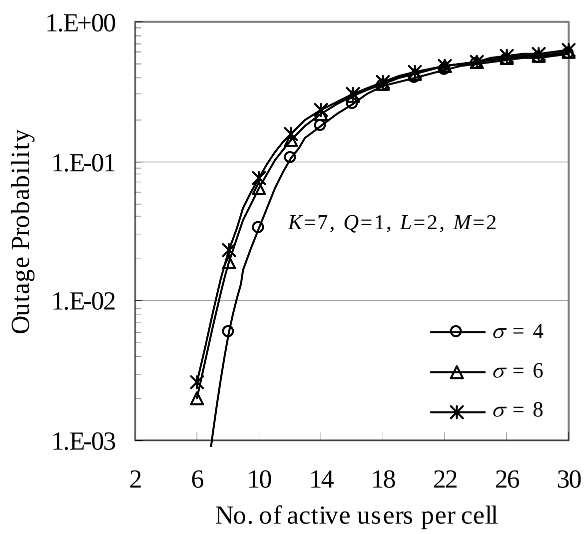

Fig. 6 Effect of shadowing loss standard deviation.

5. Conclusion

In this paper, the forward link capacity using SSDT was evaluated from the analytically derived equation employing Monte Carlo simulation. The link capacity was found to be optimal with Q=1 which is consistent with the theoretical analysis. In this case, for instance, in 2-path fading channel (L=2) with two-antenna diversity reception (M=2), 11 users can communicate simultaneously for SF=64 under the allowable outage probability of 0.1, while in case of SHO (Q=2), around 8 users can be accommodated with the same conditions as SSDT. In addition to this, it was found that an instantaneous SSDT (K>1) improves the link capacity to a great extent compared to the average power based SSDT (K=1). Antenna diversity reception has been found to contribute to further increase in the link capacity.

Path loss exponent and standard deviation of shadowing loss have also been found to have a significant effect on link capacity. These two parameters are expected to have a much larger effect on the link capacity if BS selection based on the threshold level of received signal power, cell sectorization, and the use of smart antenna etc. are taken into consideration. These are left as an interesting future study.

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Appendix: *Optimum transmit weights*

From Eqs. (13) and (14) in Sect. 3, the constraint for $\{x_q\}$ can be written as

$$\begin{cases} x_0 + x_1 + \cdots + x_{Q-1} = 1 \\ x_q \geq 0, \text{ for } q = 0,1,\cdots,Q-1 \end{cases} . \quad \text{(A1)}$$

The objective function ψ is given by

$$\begin{cases} \psi = x_0 h_0 + x_1 h_1 + \cdots + x_{Q-1} h_{Q-1} \\ \text{where } h_0 > h_1 > \cdots > h_{Q-1} > 0 \end{cases} . \quad \text{(A2)}$$

Simplex algorithm for linear programming [7] is applied to find the maximum value of ψ. Firstly x_0 is determined that satisfies $h_0 = \max_{q=\{0,1,\cdots,Q-1\}} \{h_q\}$. Replacing the right hand side of Eq. (A1) by $b_0' (= 1 \geq 0)$, Eq. (1) becomes

$$x_0 = b_0' - (x_1 + x_2 + \cdots + x_{Q-1}) \quad . \quad \text{(A3)}$$

The following relation is obtained from Eq. (2) and Eq. (A3):

$$\begin{cases} \psi = (b_0' - x_1 - x_2 - \cdots - x_{Q-1}) h_0 \\ \quad + x_1 h_1 + \cdots + x_{Q-1} h_{Q-1} \end{cases} , \quad \text{(A4)}$$

from which, we have

$$\psi - \psi_0' = x_1 h_1' + x_2 h_2' + \cdots + x_{Q-1} h_{Q-1}' \ , \quad \text{(A5)}$$

where $\psi_0' = b_0' h_0$ and $h_n' = h_n - h_0$ for n=1,2,…,Q-1. Supposing that $h_0 = \max_{q=\{0,1,\cdots,Q-1\}} \{h_q\}$, we have $h_n' < 0$. ψ is maximized only with the following condition:

$$\begin{cases} x_0 = b_0' = 1 \\ x_n = 0 \text{ for } n = 1,2,\cdots,Q-1 \\ \psi_{\max} = \psi_0' = b_0' h_0 = h_0 \end{cases} . \quad \text{(A6)}$$

Therefore, the maximum ψ and optimum x_q are given by

$$\begin{cases} x_q = \delta_{qv} \\ \psi_{\max} = h_v \text{ if } h_v = \max_{q=\{0,1,\cdots,Q-1\}} \{h_v\} \end{cases} , \quad \text{(A7)}$$

where δ_{qv} is the Kronecker's delta function [8].